

# Exotic clouds in the local interstellar medium

Snežana Stanimirović

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**Abstract** The neutral interstellar medium (ISM) inside the Local Bubble (LB) has been known to have properties typical of the warm neutral medium (WNM). However, several recent neutral hydrogen (HI) absorption experiments show evidence for the existence of at least several cold diffuse clouds inside or at the boundary of the LB, with properties highly unusual relative to the traditional cold neutral medium. These cold clouds have a low HI column density, and AU-scale sizes. As the kinematics of cold and warm gas inside the LB are similar, this suggests a possibility of all these different flavors of the local ISM belonging to the same interstellar flow. The co-existence of warm and cold phases inside the LB is exciting as it can be used to probe the thermal pressure inside the LB. In addition to cold clouds, several discrete screens of ionized scattering material are clearly located inside the LB.

The cold exotic clouds inside the LB are most likely long-lived, and we expect many more clouds with similar properties to be discovered in the future with more sensitive radio observations. While physical mechanisms responsible for the production of such clouds are still poorly understood, dynamical triggering of phase conversion and/or interstellar turbulence are likely to play an important role.

**Keywords** Interstellar medium: Physical properties · Interstellar medium: Solar neighborhood

## 1 Introduction

The diffuse interstellar medium (ISM) in the Galaxy contains structure over a wide range of spatial scales. While on scales  $\gtrsim 1$  pc we can observationally trace the entire hierarchy of structures, the extremely small-scale end of this spectrum, on scales from  $< 1$  pc to tens of AUs, is still largely unexplored. In terms of the diversity of physical properties, the diffuse neutral ISM is traditionally viewed as two types of “clouds”, referred to as the Cold Neutral

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S. Stanimirović  
Department of Astronomy, University of Wisconsin, 475 N. Charter Street, Madison, WI 53706 USA  
Tel.: +1-608-890-1458  
Fax: +1-608-263-6386  
E-mail: sstanimi@astro.wisc.edu

Medium (CNM) and the Warm Neutral Medium (WNM). The CNM and the WNM have very different temperature and volume densities, however they co-exist spatially and are expected to be (from a theoretical point of view), at least locally, in pressure equilibrium. The CNM has a temperature of  $T \sim 70$  K and a hydrogen volume density  $n \sim 40 \text{ cm}^{-3}$ , while the WNM has  $T \sim 5000$  K and  $n \sim 0.5 \text{ cm}^{-3}$  (Heiles and Troland, 2003). In terms of HI column density, the CNM has typically  $5 \times 10^{19} \text{ cm}^{-2}$  (mean value), and the WNM has  $1.3 \times 10^{20} \text{ cm}^{-2}$  (Heiles and Troland, 2003). The CNM clouds were traditionally assumed to be spherically symmetric with a size of 1-2 pc. Interestingly, recent observations are finding much larger aspect ratios.

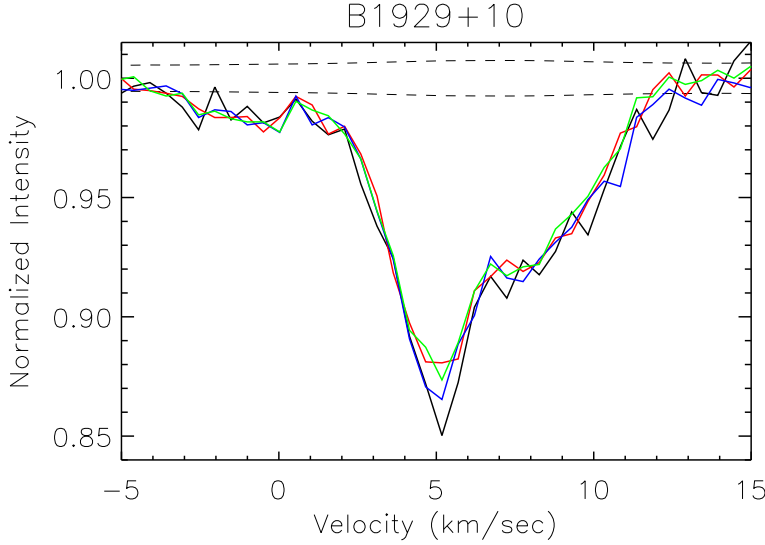
In this paper, we focus on the structure in the diffuse ISM on spatial scales of a few tens to a few thousands of AUs. We show that these features have observationally inferred properties not in accord with the traditional ISM picture, and therefore sample flavors of the most exotic diffuse ISM. In particular, we discuss the tiny scale atomic and ionized structures, and CNM clouds with very low HI column densities. Several of these exotic features are known to be very close by, inside or at the boundary of the Local Bubble (LB). The most intriguing question is whether these exotic clouds exist because they are related to the LB, or the LB has nothing to do with their existence and physical properties. We also explore how the exotic ISM compare with warm clouds within the LB, and look briefly into mechanisms that could play an important role for the formation and survival of clouds within the Local Cavity.

## 2 Tiny scale atomic structure (TSAS)

The phenomenon of Tiny Scale Atomic Structure (TSAS) was discovered in the late 1970s when interferometric observations revealed an atomic cloud with a size of 70 AUs (Dieter et al., 1976). When compared with traditional CNM clouds, TSAS has very exotic properties: a typical observed neutral hydrogen (HI) column density of  $10^{18-19} \text{ cm}^{-2}$  and a (typical) size of about 30 AU, imply a volume density  $n = 10^{3-4} \text{ cm}^{-3}$  and a thermal pressure of  $P/k = nT = 10^{4-6} \text{ cm}^{-3} \text{ K}$ . This is at least two orders of magnitude higher than what is expected for the traditional CNM. TSAS has caused a lot of controversy since its discovery as it obviously has properties grossly outside of the range expected for the ISM in pressure equilibrium. Yet, TSAS continues to be frequently encountered observationally.

How do we observe TSAS? There are several different observational methods, one being temporal variability of HI absorption spectra against pulsars. Pulsars have high transverse velocities, and typically travel over 5-50 AU per year. By comparing HI absorption spectra obtained at two different epochs we can probe density inhomogeneities on AU-scales in the CNM clouds that happen to lie between us and pulsars. This is a powerful technique, however the difference in absorption spectra we are after are tiny and therefore high resolution and sensitivity observations are essential, as well as careful instrumental calibration and data reduction.

Results from the latest study of TSAS using pulsars are presented in Stanimirovic et al. (2008, in preparation) and Weisberg and Stanimirovic (2007). These studies show that one pulsar in particular, B1929+10 (Figure 1), exhibits significant changes in HI absorption spectra at several observing epochs. The significant fluctuations, with an estimated likelihood for being real of 90-100% (for the full analysis please see Stanimirovic et al. 2008, in preparation), correspond to TSAS with a typical velocity FWHM of  $1 \text{ km s}^{-1}$ ,  $\Delta N(\text{HI}) = 10^{18} \text{ cm}^{-2}$ , and a size  $L = 30 - 45 \text{ AU}$ . If TSAS is assumed to be spherically symmetric then,  $n = \text{a few } \times 10^3 \text{ cm}^{-3}$  and thermal pressure is  $P/k = \text{a few } \times 10^4 \text{ cm}^{-3} \text{ K}$ . However, a ge-



**Fig. 1** HI absorption spectra in the direction of B1929+10 ( $l = 47^\circ$ ,  $b = -3.9^\circ$ ) obtained with the Arecibo telescope at four observing epochs. Dashed lines show a typical,  $\pm 1 - \sigma$  noise level in the absorption spectra. The absorption feature at  $5 \text{ km s}^{-1}$  has changed significantly ( $2\text{-}3\text{-}\sigma$  level) with time. For full analysis please see Stanimirovic et al. (2008, in preparation).

ometrical elongation along the line-of-sight, by a factor of  $\sim 10$ , would be able to bring the volume density and thermal pressure to what is typically expected for the CNM.

B1929+10 is the closest pulsar in our sample, at a distance of  $361 (+8, -10)$  pc (Chatterjee et al., 2004). Interestingly, the line-of-sight toward B1929+10 runs along the elongated finger of dense neutral gas bounding the LB, based on Na I observations by Lallement et al. (2003). Several studies, including Phillips and Clegg (1992), reported enhanced turbulence and scattering at the boundaries of the LB. As half of the line-of-sight to B1929+10 is either inside or along the wall of the Local Bubble, and also because this is the only pulsar in our sample that shows consistently significant fluctuations, the change in HI absorption spectra probably originates in either the presence of TSAS inside the LB or the enhanced turbulent fluctuations along the wall of the LB.

### 3 Tiny scale ionized structure (TSIS)

Analogues of TSAS exist in the ionized medium, and are called Tiny Scale Ionized Structures or TSIS. This phenomenon is observed by measuring the scattering of pulsar signals as they propagate through the intervening ionized medium. For excellent reviews of this phenomenon see Rickett (2007) and Stinebring (2007). In order to explain the observed scattering properties, two phenomena are needed in the intervening ionized medium: (i) a smooth density distribution, with random fluctuations described with a Kolmogorov spectrum; and (ii) discrete structures located along the line-of-sight, with a thickness of a few tens of parsecs (observed as “scintillation arcs” which were discovered by Stinebring et al. (2001)).

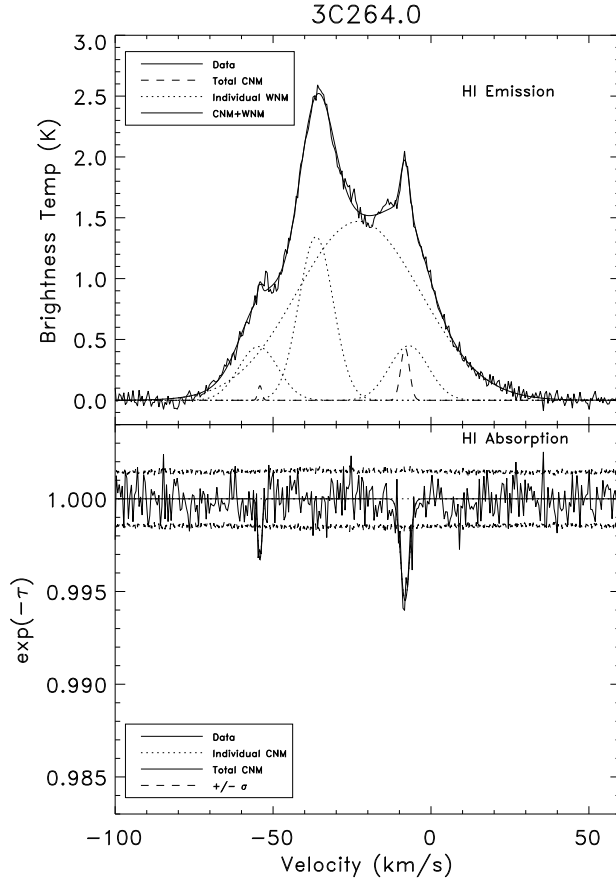
The discrete structures are often referred to as “thin scattering screens” to describe their localized and discrete nature. Furthermore, sometimes scattering screens have well-defined sub-structure (“arclets”), in the form of isolated (ionized) density fluctuations, with a size of about 1 AU and a volume density of about  $100 \text{ cm}^{-3}$  (Hill et al., 2005). The volume density of arclets is more than  $10^3$  times larger than the average electron density in the ISM and implies a high ionization fraction, with  $T \gtrsim 10^4 \text{ K}$  and  $P \sim 10^6 \text{ cm}^{-3}$  (Heiles and Stinebring, 2007).

Scintillation properties have been measured in directions to many pulsars and thin scattering screens are frequently found. If the distance to the pulsar and its proper motion are known, the location of screens along the line-of-sight can be determined. Stinebring (2007) summarizes the locations of currently known screens, and it is interesting to note that at least 6-7 screens are located inside the LB. In particular, pulsars B1929+10 and B0823+26 each have 3 screens inside the LB, while B1133+16 has a single screen at a distance of 140 pc (Trang and Rickett, 2007).

#### 4 Low column density clouds

Braun and Kanekar (2005) and Stanimirovic and Heiles (2005) recently revealed a new population of CNM clouds which have HI column densities about 50-100 times lower than typical CNM clouds. We call these clouds the “thinnest” or low- $N(\text{HI})$  clouds. Interestingly, in terms of volume density and size, low- $N(\text{HI})$  clouds occupy a regime between the traditional CNM clouds and the extreme TSAS. The work that motivated the discovery of a large sample of low- $N(\text{HI})$  clouds is the Millennium survey (Heiles & Troland 2003), which observed 79 continuum sources to establish temperature and column densities of the CNM and the WNM. Heiles & Troland (2003) noticed that 20% of their sight lines indicated either no or a very low column density of CNM. Stanimirovic & Heiles (2005) and Stanimirovic et al. (2007) used the Arecibo telescope to observe about 20 continuum sources which either had no previously detected CNM or very weak CNM features. In total, 23 new CNM clouds were detected, with a typical integration time of the order of a few hours per source. Essentially, with long integration times weak HI absorption lines emerge easily. As an example, Figure 2 shows one of the sources, 3C264.0, where two new CNM clouds were found with a peak optical depth of  $5 \times 10^{-3}$  and  $3 \times 10^{-3}$ , or an HI column density of  $9 \times 10^{18}$  and  $5 \times 10^{17} \text{ cm}^{-2}$ , respectively. Clearly, these HI column densities are among the lowest ever detected for the CNM. Another, not so extreme example is shown in Figure 3, where a single new CNM cloud is detected at a LSR velocity of  $-0.8 \text{ km s}^{-1}$ .

There are several important points emerging from recent studies. (i) The detection rate of the Stanimirovic et al. (2007) experiment is very high, suggesting that weak HI absorption features are common in the ISM. Essentially, we just need to integrate long enough. (ii) The preliminary addition of the new population of CNM clouds to the “traditional” CNM population by Heiles & Troland (2003) resulted in the combined column density histogram that can be easily fitted with a single function,  $\propto N(\text{HI})^{-1}$ . This suggests that low- $N(\text{HI})$  clouds most likely do not represent a separate population, but could simply be a low column density extension of the traditional CNM. (iii) However, the low- $N(\text{HI})$  clouds are probably smaller than typical CNM clouds. If we assume an equilibrium pressure of  $3000 \text{ cm}^{-3} \text{ K}$  and a volume density of about  $40 \text{ cm}^{-3}$ , we can estimate a cloud line-of-sight size of about 800-4000 AU. If over-pressured, clouds would have even smaller line-of-sight length. (iv) The low- $N(\text{HI})$  clouds have an extremely low ratio of the CNM to total HI column density,  $< 5\%$ . This suggests that cold low- $N(\text{HI})$  clouds are most likely surrounded by a large

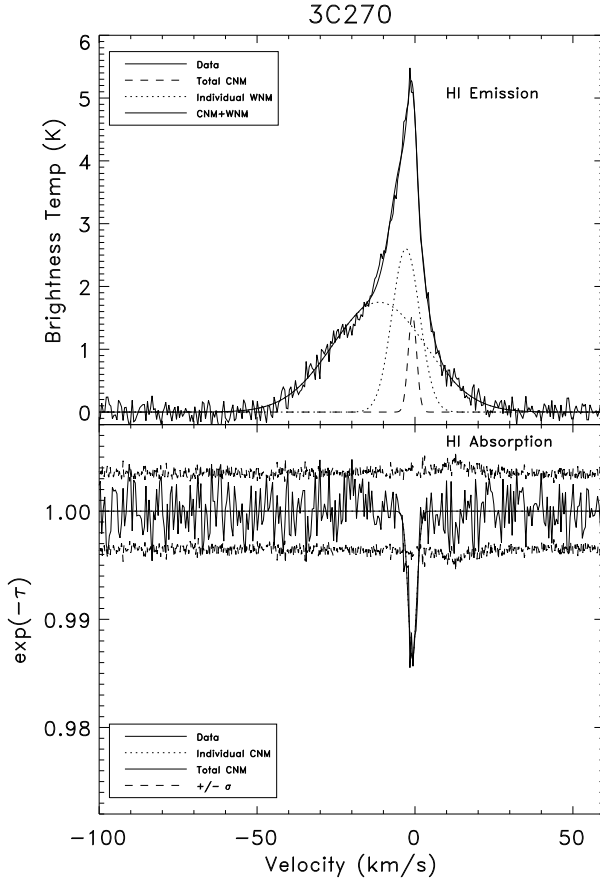


**Fig. 2** HI emission and absorption spectra in the direction of 3C264.0, obtained with the Arecibo telescope (Stanimirovic, De Back et al., in preparation). Two new CNM components were detected. The top panel shows the HI emission profile with separate contributions from the CNM and WNM shown as dashed and dot-dashed lines, respectively, while the final (simultaneous) fit is shown with the thick solid line. The middle panel shows the HI absorption spectrum with two fitted Gaussian components, with dotted lines representing  $\pm 1 - \sigma$  noise level. The decomposition of HI emission and absorption spectra into Gaussian components was performed to estimate the HI spin temperature, employing the method of Heiles and Troland (2003).

amount of warmer gas. This may be important for cloud survival by providing a blanket against evaporation.

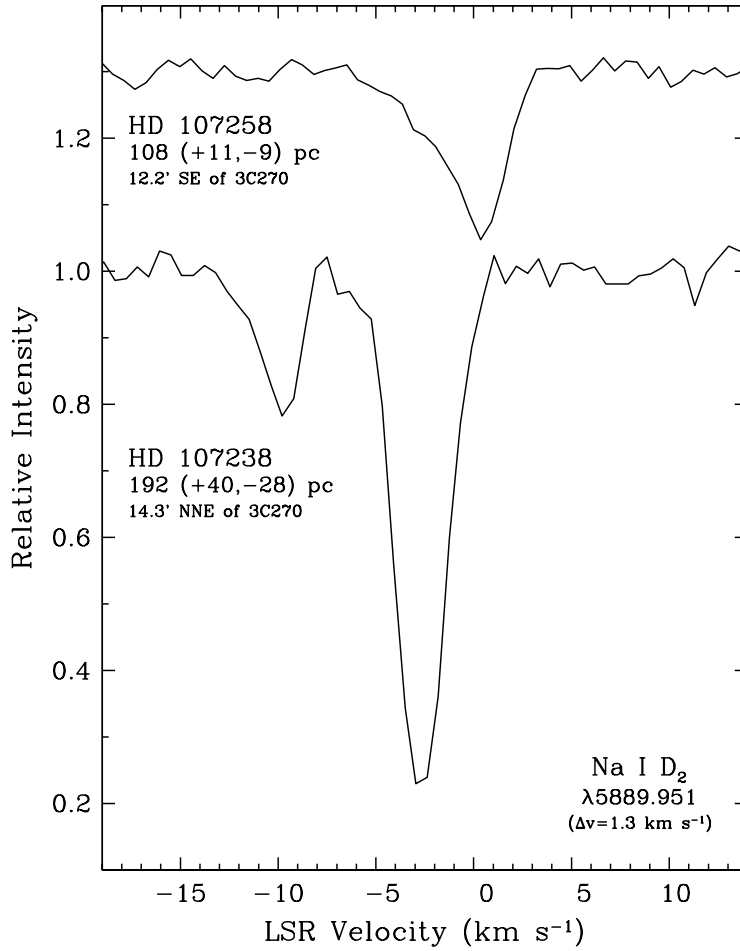
## 5 Cold clouds inside the Local Bubble

For one of the low- $N(HI)$  clouds (3C270,  $l = 184.8^\circ$   $b = 5.8^\circ$ ) we have obtained recently Na I absorption spectra in directions of two close by stars with known distances (Meyer &



**Fig. 3** HI emission and absorption spectra in the direction of 3C270, obtained with the Arecibo telescope. One CNM component was detected. Plotted quantities are the same as in Figure 2.

Stanimirovic, in preparation). As shown in Figure 4, in the direction of star HD 107258, which is 12 arcmin to the south-east from 3C270 and at a distance of 108 (+11, -9) pc, an absorption feature was detected at a LSR velocity of  $0.55 \text{ km s}^{-1}$  and with a velocity FWHM of  $3\text{--}4 \text{ km s}^{-1}$ . The HI absorption spectrum in Figure 3 shows a feature at a velocity of  $-0.8 \text{ km s}^{-1}$ , with a velocity FWHM of  $3.2 \text{ km s}^{-1}$ . The two absorption features most likely trace the same interstellar gas. This suggests that the local HI absorbing gas, seen in Figure 3, is likely to be located within 100-120 pc from the Sun. In this direction, Na I observations by Lallement et al. (2003) suggest that the boundary of the LB, with  $N(\text{HI}) > 10^{20} \text{ cm}^{-2}$ , is at a distance of  $\sim 130 \text{ pc}$ . Therefore, the HI cloud in the direction of 3C270 could easily be lying within the Local cavity. This is a cold HI cloud, with the velocity linewidth of only  $3.2 \text{ km s}^{-1}$ , the estimated spin temperature of 115 K, and the peak HI column density of  $10^{19} \text{ cm}^{-2}$ . As the  $0.55 \text{ km s}^{-1}$  absorption feature is absent in the Na I spectrum of HD 107238, a



**Fig. 4** Na I absorption spectra in the direction of 3C270. HD 107258 is located 12 arcmin to the south-east from 3C270 and is at a distance of 108 pc, while HD 107238 is 14 arcmin to the north-east from 3C270 and at a distance of 190 pc. Spectra were obtained with the 0.9 m coude feed telescope and spectrograph at Kitt Peak National Observatory.

star which is 14 arcmin to the north-east from 3C270 and at a distance of 192 (+40, -28) pc, the spatial extent of the HI absorbing cloud maybe only  $\sim 0.3\text{-}0.4$  pc. Figure 4 also shows a strong Na I absorption feature at a velocity of  $-2.5 \text{ km s}^{-1}$  seen only in the spectrum against the more distant star and without a corresponding HI absorption. This (warmer) cloud is likely to be at a distance of 110–190 pc. Followup observations of several stars around 3C270 are underway with the Kitt Peak 3.5m telescope to constrain better cloud distances.

Another especially clear example of a cold HI cloud found inside the LB was studied by Meyer et al. (2006). This Leo cloud holds a double record, being the coldest diffuse cloud with a spin temperature of only 20 K, and at the same time the closest diffuse cloud with a firm upper distance limit of 45 pc (constrained using 33 stars with known distances). If in pressure equilibrium with  $P = 2300 \text{ K cm}^{-3}$ , it has a size of  $1.4 \times 4.9 \times 0.07$  pc, being

**Table 1** Approximate properties of clouds inside the Local Bubble.

| Type                | Temperature (K) | Density $\text{cm}^{-3}$ | Size (AU)   | Ionization state  |
|---------------------|-----------------|--------------------------|-------------|-------------------|
| CNM                 | 100             | 40                       | $10^5$      | neutral           |
| TSAS                | $\lesssim 100$  | $10^{3-4}$               | 10-100      | neutral           |
| TSIS                | $\gtrsim 10^4$  | $10^2$                   | 1           | ionized (arclets) |
| low- $N(\text{HI})$ | $\lesssim 100$  | $10^2$                   | 800-4000    | neutral           |
| CLIC                | 6800            | 0.2                      | $\sim 10^5$ | partially ionized |

more ribbon-like than spherically symmetric. It is worth noting that a thermal pressure close to the standard ISM pressure was assumed and this resulted in the pc-scale size of the cold cloud (a higher thermal pressure would decrease the cloud size).

The Riegel-Crutcher cloud is another cold, highly filamentary cloud, that appears to be located right at the edge of the LB (Crutcher and Lien, 1984; McClure-Griffiths et al., 2006). This cloud extends over  $\sim 40$  degrees of Galactic longitude ( $l = 5^\circ$  to  $355^\circ$ ) and  $\sim 10$  degrees of latitude ( $b = -5^\circ$  to  $5^\circ$ ). It has a distance of  $125 \pm 25$  pc, a size of  $80 \times 20 \times (1-5)$  pc, and a HI spin temperature of 40 K. If filaments are cylindrical with the thickness similar to their plane-of-sky width of 0.1 pc, then they have an average volume density of  $450 \text{ cm}^{-3}$  and a thermal pressure of  $2 \times 10^4 \text{ K cm}^{-3}$ . However, an edge-on ribbon geometry would imply a line-of-sight thickness of 1 pc, an average volume density of  $46 \text{ cm}^{-3}$ , and a thermal pressure of  $2 \times 10^3 \text{ K cm}^{-3}$ .

## 6 Comparison with the Cluster of Local Interstellar Clouds

The cluster of local interstellar clouds (CLIC) is a clumpy flow of warm, low-density material inside the LB, and within 35 pc from the Sun. Table 1 provides a summary of basic properties of CLIC and clouds discussed in previous sections. Further from the Sun, within 350 pc, the ISM includes low-density, hot gas inside the LB, but also a range of clouds with cooler temperatures. For example, Welty et al. (1999) found four neutral, cold ( $T \sim 100$  K) and dense ( $N(\text{HI}) \sim 10^{20.7} \text{ cm}^{-2}$  and  $n \sim 10-15 \text{ cm}^{-3}$ ) clouds, and many warm ( $T \sim 3000$  K), dense ( $n \sim 15-20 \text{ cm}^{-3}$ ) clouds.

While CLIC clouds have column densities similar to those of TSAS and low- $N(\text{HI})$  clouds, they are significantly warmer and more ionized. In terms of fractional ionization, CLIC is intermediate between the WNM and the warm ionized medium (Dickey, 2004). Müller et al. (2006) compared the HI column density and the LSR velocity of CNM and WNM clouds at high Galactic latitudes (from Heiles & Troland 2003) with those of CLIC clouds within 50 pc of the Sun. While CLIC clouds have typically a low HI column density ( $N(\text{HI}) < 10^{19} \text{ cm}^{-2}$ ), their kinematic properties appear similar to those of WNM clouds. The central velocity of the majority of low- $N(\text{HI})$  clouds is in the range  $-17$  to  $10 \text{ km s}^{-1}$ , and the column density range is  $3 \times 10^{17}$  to  $4 \times 10^{19} \text{ cm}^{-2}$ . In terms of column density and kinematics, low- $N(\text{HI})$  clouds (as well as the cold Leo cloud and the TSAS clouds in the direction of B1929+10) and CLIC occupy a very similar parameter space. This may suggest that all these clouds belong to the same interstellar flow.

Table 2 provides a summary of exotic clouds inside or at the boundary of the LB. Clearly, Leo cold clouds are undoubtedly inside the LB. The low- $N(\text{HI})$  cloud in the direction of 3C270 and the TSAS cloud(s) in the direction of B1929+10 are very likely to be located inside the



**Table 2** Summary of exotic clouds inside or just outside of the Local Bubble.

| Object            | Distance (pc)       | Type         | Comment  |
|-------------------|---------------------|--------------|--|
| B1929+10 cloud(s) | < 360               | TSAS, TSIS   | cold clouds inside/edge of LB, several scintillation screens |
| B1133+16 screen   | 140                 | TSIS         | scintillation screens (Trang and Rickett, 2007), no TSAS     |
| 3C270 cold cloud  | $\lesssim 100$ -120 | low- $N(HI)$ | most likely inside LB  |
| Leo cloud         | $\lesssim 45$       | CNM          | clearly inside LB  |
| R-C cloud         | 125                 | CNM          | at the edge of LB  |

LB. In addition, several TSIS scintillation screens are clearly located inside the LB. The key question is whether warm and cold clouds inside the LB are physically related. For example, could CLIC clouds represent warm envelopes of colder TSAS and low- $N(HI)$  clouds? And, could scintillation screens represent ionized fronts of CLIC? As hinted in Section 4, there is evidence for the existence of large warm envelopes around low- $N(HI)$  clouds. The existence of cold clouds inside the LB with kinematic properties similar to those of CLIC rises an exciting possibility that at least some cold clouds are physically co-located with CLIC. Based on heating and cooling considerations, the co-existence of warm and cold phases requires a well-defined range of thermal pressures. Hence, future distance measurements of low- $N(HI)$  clouds may allow us to constrain better the thermal pressure inside the LB.

## 7 Formation and survival of cold clouds

Is it surprising to find cold clouds inside the LB? At first glance, we would expect that cold “thin” clouds would be subjected to the heat from the surrounding hot medium and be eaten away by evaporation very quickly. However, careful consideration of conductive heat transfer, especially in the small-scale regime, suggests that such clouds are surprisingly long-lived although are most likely undergoing evaporation. Their typical evaporation timescale is of order of  $10^6$  yr (see Stanimirovic & Heiles 2005 for details; also Slavin (2007)). If surrounded by large WNM envelopes (as suggested in Section 4), and/or magnetic field, the clouds would be even longer lived, and therefore could be common in the local ISM.

However, physical mechanisms responsible for the production of such clouds in the ISM in general are not well understood. There are several potentially interesting theoretical avenues that await a closer comparison with observations.

*Condensation of WNM into CNM triggered by the collision of turbulent flows* is capable of producing a large number of small CNM clouds with low column densities, as seen in simulations by Audit and Hennebelle (2005) and Hennebelle and Audit (2007). The CNM clouds produced in simulations are thermally stable and embedded in large, unstable WNM filaments, their typical properties are:  $n \sim 50 \text{ cm}^{-3}$ ,  $T \sim 80 \text{ K}$ ,  $R \sim 0.1 \text{ pc}$ . The number of cold clouds, as well as their properties, depend heavily on the properties of the underlying turbulent flows. Within this scenario, exotic cold clouds inside the LB may be remnants of collisions between warmer CLIC clouds.

*General ISM turbulence* envisions interstellar clouds as dynamic entities that are constantly changing in response to the turbulent “weather”, a picture very different from the traditional approach. Numerical simulations of turbulent ISM, for example Vazquez-Semadeni et al. (1997) show many clouds with very small sizes and low column densities ( $< 10^{19} \text{ cm}^{-2}$ ).

These clouds are out of dynamical equilibrium and probably very transient. In this scenario, the exotic cold clouds may be a tail-end of the turbulent spectrum of general ISM clouds.

*CNM destruction by shocks* in simulations by Nakamura et al. (2006) can also produce a spray of small HI ‘shreds’ that could be related to low- $N(\text{HI})$  clouds. These shreds are expected to have large aspect ratios, up to 2000. As several successive supernova explosions have been postulated to be responsible for the formation of the LB (Breitschwerdt and de Avillez, 2006), it would not be hard to imagine shock interactions with clouds inside the LB and the production of exotic cloudlets. Similarly, Breitschwerdt & de Avillez (2006) suggest that the interaction between shells that bound bubbles caused by supernova explosions can drive Rayleigh-Taylor instability and the formation of cloudlets.

## 8 Conclusions

We have summarized evidence for the existence of at least several exotic clouds inside or just outside the LB. The importance of these clouds is twofold. Firstly, they provide extreme examples of the interstellar clouds that the Sun may encounter over a timescale of several million years. As shown by Müller et al. (2006), highly dense and cold clouds would have a significant effect on the size of the heliosphere. Secondly, studies of different phases of the very local ISM can shed some light on the properties and the formation mechanism of the LB.

The cold exotic clouds (TSAS and low- $N(\text{HI})$  clouds) have AU-scale sizes and low HI column densities. While TSAS has high HI volume density and thermal pressure, low- $N(\text{HI})$  clouds are in this regard similar to traditional CNM clouds. While significantly colder and less ionized than CLIC, the exotic (cold) clouds agree well with CLIC clouds in terms of HI column density and kinematics. This may suggest the physical co-existence of different populations, however distances of most of low- $N(\text{HI})$  clouds are unknown. If physically co-located, these clouds would imply a well-defined range of thermal pressures inside the LB. Future distance constraints of cold clouds are essential to explore this avenue.

While most likely undergoing thermal evaporation, cold exotic clouds inside the LB could last for a long time. Therefore, it is not surprising to encounter them frequently. However, their production mechanisms are still not understood. Potential avenues highlight the importance of dynamical triggering of phase conversion (through collision of warm clouds or interaction of shocks with warm clouds), and interstellar turbulence.

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